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STRUCTURE AND PROPERTIES OF INTERLAYER FORMED BETWEEN MAGNESIUM ALLOY CORE AND ALUMINIUM ALLOY COATING DURING DEFORMATION

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Abstract

The article focuses on the analysis of the properties of an interlayer formed between the magnesium (AZ91) alloy core and aluminium (6101) alloy coating during compression and extrusion at 350°C. Different variants of the coated layer thickness and of the extrusion process parameters were used.
As a result of the tests carried out and the deformation applied, a uniform and consistent interlayer bond was produced. The interlayer width was about 5 μm and it was composed of two sub-layers with a width of about 4 μm and 1μm. The analysis of the chemical composition of the sub-layers carried out on SEM with EDS indicates that these are probably the $Al_{12}Mg_{17}$ and Al_3Mg_2 phases. Rods extruded from the AZ91 magnesium alloy with proper aluminium alloy coating were found to offer an increase in the strength properties of about 20% compared with properties of the sole AZ91 alloy. On specimens selected for SEM, the tensile fracture surfaces were also examined.

Introduction

Nowadays researches tend towards wrought magnesium and aluminium alloys and their large scale application. The greatest advantage of both these alloys is their low weight-to-volume ratio [1-5]. Although magnesium is lighter than aluminium by about 35 %, some of its properties, such as melting point and strength, are in both cases similar. The only feature that is different in these two alloys is their ductility resulting from the limited number of slip systems in magnesium [2]. Additionally, compared to aluminium, magnesium has a reduced modulus of elasticity. In spite of all the benefits that magnesium alloys can offer, their use in mass car production is very limited due to the very poor corrosion resistance of the wrought stock [4, 5, 6]. The corrosion resistance of aluminium alloys is definitely superior to that of magnesium alloys; they also tend to get coated with an oxide film that forms a layer of Al_2O_3, naturally protecting the surface from the effect of corrosive agents [3]. Hence the idea was born to use the commonly applied aluminium alloys as a protective coating on Mg profiles [1]. Studies conducted by two independent research centres [1, 3] have stated the possibility of producing a fast bond between aluminium and magnesium alloys during plastic working.
As a result of the extrusion process carried out at a temperature of 350°C, closed profiles of a rectangular cross-section having as a top layer the aluminium alloy coating and magnesium alloy as a core were produced. Similar situation occurs in the case of cold-rolled magnesium alloy sheets with the top layer of aluminium alloy, where as a result of the force acting and an annealing process above 250°C, a bond composed of the Al_3Mg_2 phase is produced. The Al_3Mg_2 phase is a hard intermetallic formed between the soft aluminium and magnesium alloys, enhancing further their durability [3].
The aim of the present research was to obtain in the extrusion process a layer of plating characterised by a consistent and uniform bond and a best combination of the mechanical properties. To examine the bond behaviour, a sample rod made of the AZ91 magnesium alloy with coating made of the 6101 aluminium alloy was subjected to a compression process and then examined for its principal characteristics. The influence of the plating process on the coherence and strength properties of the plated product was examined.

Experimental Procedure

In the first part of the study, samples of two alloys were prepared, i.e. the 6101aluminium alloy, which was used for the coating, and the AZ91 magnesium alloy of which the core was made. The samples were subjected to compression test on an Instron 100kN machine. The sample size was ϕ 10x20, this including thickness of the aluminium alloy coating (a "sleeve"), which was 3 mm. The 6101 aluminium alloy "sleeve" was first etched to remove oxides from its interior, and then a rod of AZ91 alloy was press fitted into it on the testing machine. The whole was compressed at 350°C up to 80 % deformation. After the compression test, the structure was examined under a Philips XL30 scanning electron microscope with attachments for the EDS chemical analysis and EBSD crystallographic analysis. A Tecnai G^2 TEM with an attachment for the EDS chemical analysis by STEM was also used. In the second part of the study, the extrusion tests were made on a vertical press with 250T capacity. From the 6101 alloy, hollow sleeves of ϕ 28mm diameter and a wall thickness of 5 mm, 3 mm and 1 mm were made. As in the compression test, they were also subjected to etching to remove the oxide film. Into thus prepared sleeves, the AZ91 alloy cores were press fitted. The total length of the sample was 50 mm. All samples were extruded in a direct system at a temperature of 350°C yielding rods with a diameter of ϕ 8mm. The resulting rods were subjected to structure analysis to examine the bond consistency and uniformity under an optical microscope. Using an Instron 100kN testing machine, a uniaxial tensile test was carried out, examining the sample fracture topography under a scanning electron microscope. Samples for both optical and scanning electron microscopy were prepared by grinding and polishing to obtain proper metallographic sections. Samples for the EBSD and TEM analysis were prepared by ion thinning.

Results

The trials of joining magnesium alloy with aluminium alloy enabled determining the optimal conditions under which the Al/Mg bond is produced. Structure examinations were carried out, including identification of intermetallic phases formed at the interlayer boundary with an assessment of their thickness. Further studies included trials carried out during the extrusion process to optimise the properties of the obtained bonds.

Characterisation and quality assessment of the Mg/Al bond produced by compression

During compression of the sample at 350°C, a uniform Al/Mg bond composed of intermetallic phases was produced. By scanning electron microscopy, the chemical composition of the bond was examined (Fig. 1). The results of this examination show that the transition between the alloys is separated by an interlayer 5 to 6 µm thick, where the lines of Al and Mg content are intersecting.

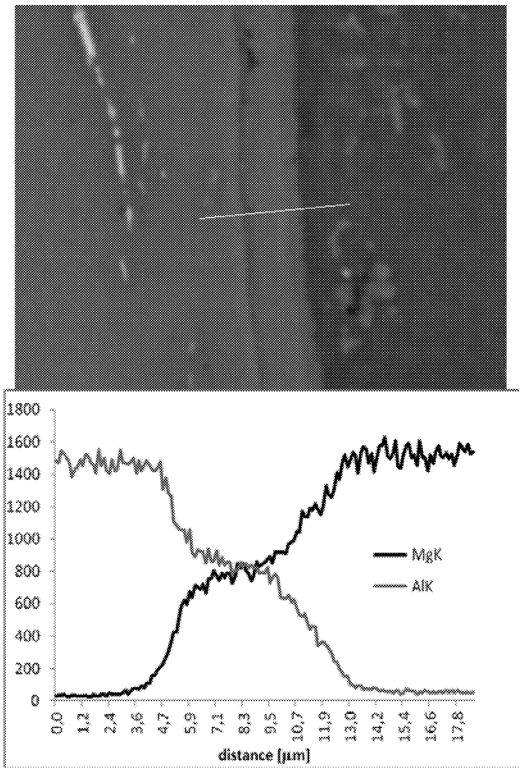
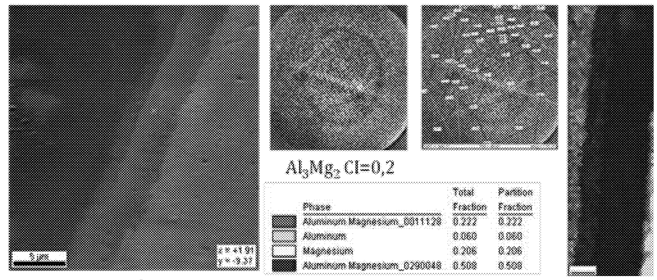


Fig. 1 Chemical linear analysis of the interlayer in samples after compression.

The results of the examinations made by EBSD, also including local analysis of the chemical composition, indicate the diffusion-aided formation of two phases present in the Al-Mg equilibrium system (Fig. 2). This was the Al_3Mg_2 phase of a thickness of about 4 - 5 µm and the second, substantially narrower, $Al_{12}Mg_{17}$ phase of a thickness of about 1 µm. The Al_3Mg_2 phase was formed on the side contacting aluminium alloy and is running in parallel direction through the entire length of an interlayer obtained in the examined sample. The $Al_{12}Mg_{17}$ phase is narrow and, along the interlayer length, shows some non-uniformities on the side contacting magnesium alloy. In some places of the interlayer it is wider than in the others. The interlayer connection as a whole was free from the cracks, was uniform and running through the entire length of the examined sample. Additionally, the microstructure of the interlayer was examined by transmission electron microscopy (Fig. 3), and it was found that the structure of Al_3Mg_2 and $Al_{12}Mg_{17}$ phases were fine-grained and coherent on the side of both aluminium and magnesium alloys. In both phases, the grain size was less than 1 mµ. In the image of microstructure



Phases	Description
$Al_{12}Mg_{17}$ (red)	[%at] Mg – 53, Al – 32, Si, O, C ICDD PDF file no. 0011128; cubic (0h)[m3m], a=10,56Å
Al_3Mg_2 (blue)	[%at] Mg – 33, Al – 57, Si, O, C ICDD PDF file no. 0290048; cubic (0h)[m3m] a=28.239Å
Al (green)	cubic (Oh)[m3m] a=4,04Å
Mg (yellow)	hexagonal (D6h)[6/mmm] a=3,2Å; c=5,2Å

Fig. 2 EBSD phase analysis combined with local chemical analysis of the Mg/Al interlayer after compression.

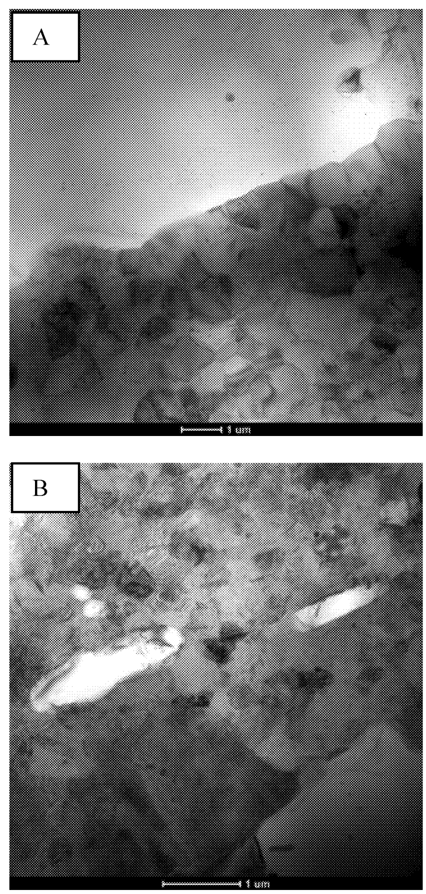


Fig. 3 TEM microstructure of the interlayer: a) on the side of the AZ91 magnesium alloy, and b) on the side of the 6101aluminium alloy.

it was difficult to distinguish between the two phases. However, inside the grains of the Al_3Mg_2 phase, twinned crystals were noted to occur (Fig. 4). In certain areas inside the grains, the density of dislocations was high, the precipitates were coarse, and some oxides appeared. From the analysis of the chemical composition it followed that, in addition to Al and Mg, the large precipitates also contained elements such as Fe and Si.

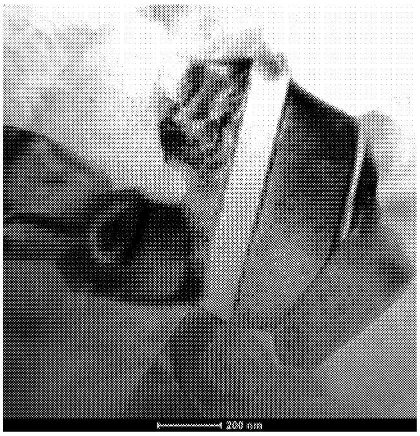


Fig. 4 Grains of the Al_3Mg_2 phase.

Evaluation of the properties of plated AZ91 alloy rods after the process of direct extrusion

In the process of plastic working carried out at 350°C, rods were extruded from the AZ91 alloy with the 6101 alloy coating characterised by varying thickness of 5mm, 3mm and 1mm. The obtained plated rods were examined for the bond quality and plastic flow of the rod material with coating. The first to analyse was the material flow behaviour in a die. For this purpose, the microstructure in the end part of the extrudates (so called flashes) was examined (Fig. 5). It was found that plating took place in the die, and the larger was the thickness of the coating on the feedstock, the more of 6101 alloy accumulated in the dead zones of the die at the end of the extrusion process. This situation can lead to curling of the Mg alloy feedstock when processed on large presses.

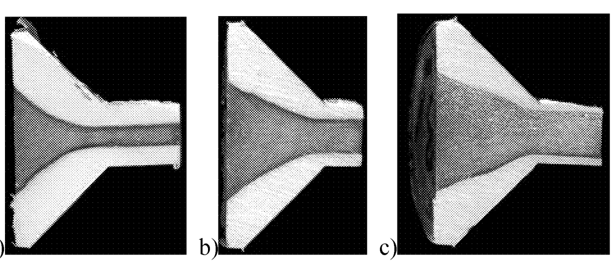


Fig. 5 Cross-sections of the end parts of the successive sample extrudates with the coating thickness of: a) 5 mm, b) 3mm c) 1 mm.

The interlayer connection was uniform on the entire length of the extruded rods and showed no cracks. The defect in the extruded rods was uneven coating thickness, varying in the starting, middle and end part of the rod (Fig. 6). It was observed that rods in the starting part were totally deprived of coating, the plating thickness in the middle part varied and, depending on the coating thickness, ranged from 300 to 500 μm. The situation was similar in the end part of the extruded rods, but in this case the plating thickness exceeded 1 mm.

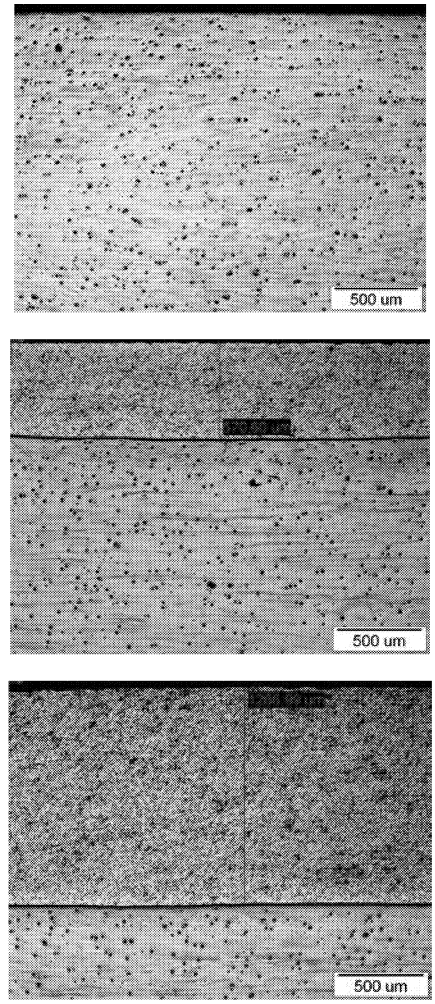


Fig. 6 Microstructure on the rod cross-section with the coating of 3 mm thickness: a) the starting part, b) the middle part, c) the end.

The mechanical properties were examined in a uniaxial tensile test carried out on rods, analysing also the quality of bond on a sample fracture. The results of mechanical tests (average of two measurements) are presented in Table I. Based on these results, it was found that the thinner was the layer of plating, the more important was the role of the intermetallic layer in the strengthening process, hardening further the AZ91 alloy core.

Table I The results of a uniaxial tensile test carried out on plated rods.

Series	$R_p0{,}2$ [MPa]	R_m[MPa]	A [%]
5mm	134	214	23
3mm	165	248	-
1mm	171	292	20,6

All the samples examined showed an uneven mode of fracture (Fig. 7). The height at which the fracture occurred differed for the aluminium alloy, magnesium alloy and an intermetallic phase. Topographic analysis of rods after the tensile test showed three types of fractures: coating - ductile aluminium alloy, core -

magnesium alloy and, not visible in the image, structure of the brittle Al_3Mg_2 and $Al_{12}Mg_{17}$ phases.

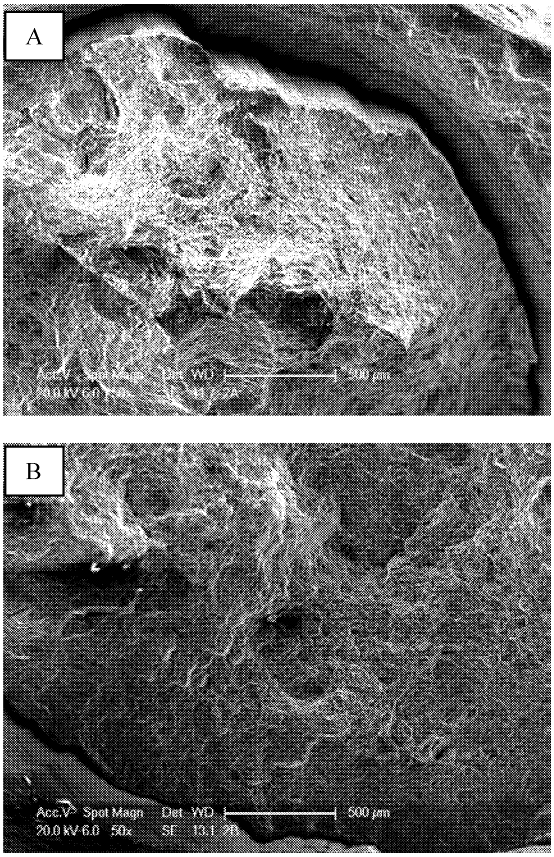


Fig. 7 Rods fracture topography after the extrusion of feedstock with plating thickness of a) 5 mm and b) 3mm.

Conclusions

In the sample after compression at 350°C, a coherent bond between the magnesium alloy and aluminium alloy was obtained. The interlayer was composed of two phases, i.e. Al_3Mg_2 and $Al_{12}Mg_{17}$ - one with a thickness of 4 to 5 µm, and the other with a thickness of about 1 µm. It was found that thickness of those phases was determined by the coefficient of interdiffusion - higher by one order of magnitude for the Al_3Mg_2 phase compared with the $Al_{12}Mg_{17}$ phase, thus making growth of the Al_3Mg_2 phase much easier. Only when the diffusion process is hindered at the phase boundary, proper conditions for the nucleation of $Al_{12}Mg_{17}$ phase on the Al_3Mg_2/Mg phase boundary are created [7].

Using a 250T forging press, at a temperature of 350°C, rods of ϕ8mm cross-section were extruded in a direct process from the AZ91 alloy with coating made of the 6101 alloy. The interlayers obtained in the three tested samples with different coating thickness (5mm, 3mm, and 1mm) were uniform and coherent on the entire length of the rods, showing no cracks.

The aluminium alloy plating thickness on the rod length was uneven. Differences occurred between the starting and end part of the rod. The reason for these differences can lie in the mode of extrusion. Changing the direct extrusion mode into an indirect one can contribute to the fabrication of plating layer of a uniform thickness on the entire length of the rod.

Studies of the surface topography of samples after the tensile test showed significant differences in the necking formation in the three different materials (AZ91 phases: Al_3Mg_2, $Al_{12}Mg_{17}$ and 6101). The reason is that these materials have different mechanical properties. Additionally, thinning of the aluminium alloy plating contributes to obtaining higher mechanical properties.

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